NASA TECHNICAL TRANSLATION NASA TT F-14,257

ACOUSTICAL CONTROL OF TURBULENT EXCITATION IN FREE JETS

O. Wehrmann

Translation of: "Akustische Steuerung der Turbulenten Anfachung im Freistrahl", Wissenschaftliche Gesellschaft für Luftfahrt, 1957 yearbook, pp. 102-108.

(NASA-TT-F-14257) ACOUSTICAL CONTROL OF TURBULENT EXCITATION IN FREE JETS O. Wehrmann (Scientific Translation Service) Apr. 1972 17 p CSCL 20D
N72-22331
Unclas
G3/12 24247

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 APRIL 1972

CAT. 12

ACOUSTICAL CONTROL OF TURBULENT EXCITATION IN FREE JETS*

Ottmar Wehrmann,
Berlin

ABSTRACT. Experiments in the boundary layer of a free jet behind a nozzle, at Reynolds numbers up to 20,000 are discussed. The possibility of influencing the conditions of flow acoustically are realized during measurements employing the hot-wire method, primarily without artificial disturbances. The ring vortices which form downstream behind the nozzle initiate the state of fully developed turbulence and can be assessed, in accordance with the hot-wire method by four characteristic properties: /102**

1. measuring the field of mean velocities (measurement of $\bar{c}$);

2. taking the curve of excitation and the strength Γ of the ring vortices (measurement of c' and c_ϕ respectively);

3. finding the relation between the frequency of the ring vortices and the velocity of the flow (frequency theorem);

4. finding the distance between two ring vortices (measurement of the wavelength λ).

In order to be able to study the stability of the free jet and, in particular, the free boundary layer as it governs the effects behind the nozzle exit, the acoustic effect was chosen as the means for artificial disturbance from a loudspeaker outside of the field of flow. The following results were obtained:

---

*From the Institute for Turbulence Research of the German Test Facility for Aeronautics, Berlin-Charlottenburg.

**Numbers in the margin indicate pagination in the original foreign text.

(a) The separation of the vortices can be influenced by the sound energy, superimposed on the boundary layer. At a constant velocity of flow the so-called "natural frequency" of the vortices can be "carried away" over a certain region. The results are similar to those of the well known stability curves for the boundary layer over a flat plate as given by Tollmien, Schlichting and Lin.

(b) The strength Γ of the ring vortices close behind the nozzle exit can be considerably increased by acoustic influence. Since the position of the lines of mean velocities $\bar{c}$ is given by the exchange of momentum of the ring vortices, a considerable change of the entire field of flow is obtained.

(c) Applying feedback coupling, a curve can be found for the maximum frequency of excitation by first directing the amplified hot-wire signals back into a loudspeaker which retransmits the signals.

(d) The speed of vortex transportation u_v as affected by acoustics can be found from measuring phase and frequency. At a constant velocity of flow the wavelength is shown to remain constant, whereas the velocity of vortex transport changes.

1. INTRODUCTION

/102

The connection between tones or noises on the one hand and flow processes at the air exit slits or knife edges, on the other hand, has been investigated for about 100 years. Various authors have addressed themselves to a variety of questions. Already in 1858, J. Leconte [1] observed periodic vortex formations and oscillating motions of the gas jet of a burner. The entire flow field is influenced by acoustic phenomena. The experiments of G. Brown [2, 3] also are concerned with these problems, which resulted in a frequency law for the vortex formation.

Modern research has addressed itself to the question of the connection between the turbulence and the noise which dominate the flow process. The first theoretical treatment of this complex was given by M. Lighthill [4] and the corresponding experimental investigations are due to L. W. Lassiter and H. H. Hubbard [5] as well as A. Powell [6]. The investigation of the so-called Pfeifenton was carried out by A. Anderson [9, 10]. In addition, the investigation of vortex phenomena in the boundary layer and especially in the free boundary layer of a jet emerging from a nozzle has become important for the excitation of disturbances. The papers by U. Domm [7], O. Wehrmann and R. Wille [8] are concerned with these problems.

The following investigations refer to these boundary layer processes up to a Re number of 20,000, referred to the nozzle diameter. It is shown how the excitations due to finite disturbances can be controlled acoustically.

2. FLOW PROCESSES BEHIND A NOZZLE FOR SMALL REYNOLDS NUMBERS WITHOUT ACOUSTIC INFLUENCE

2.1. Measurements According to the Colored Thread Method

The flow process phenomena were first investigated in a water tank, and the boundary layer was colored according to the colored thread method.

The upper part of the photograph in Figure 1 shows four different regions which characterize the flow process. First of all on the left there is a line which is labeled I which represents the laminar boundary layer behind the nozzle. This laminar boundary layer rolls up in the form of discrete vortices (II). These ring vortices increase in intensity and begin to wander around each other (III). After the wandering process, two ring vortices join to form one which then decays after a certain path distance (indicated by IV). All the investigations described in the following only treat the region in which the laminar boundary is formed up to the point where the ring vortex, which is formed from two individual vortices, decays.

2.2. Measurements According to the Hot-Wire Method

Even though the colored thread method results in very clear pictures in the water, it is very difficult to carry out an accurate evaluation of the

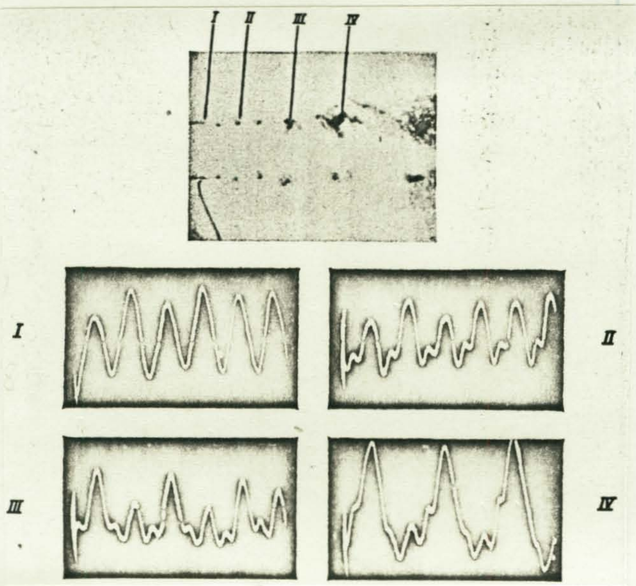

Figure 1. Colored thread and hot-wire signals behind a nozzle outlet.

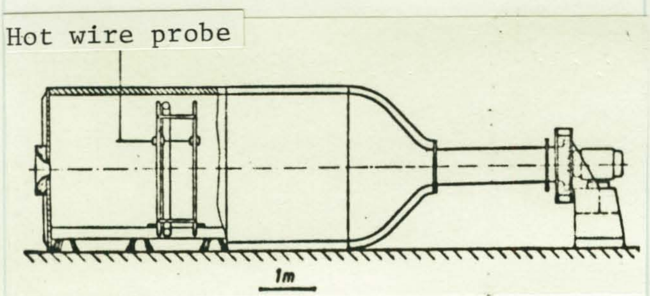

Figure 2. Underpressure chamber for hot-wire measurements.

overall results. This is why the measurements were carried out in air using the hot-wire measurement technique. A hot wire having a diameter of 1.5 μ and a length of 0.5 mm was used for the measurements, which makes it possible to carry out an exact analysis. An underpressure chamber was used for the experiment (Figure 2). Various nozzles could be mounted along its frontal plane. /103

According to the hot-wire measurement technique and using a turbulence measurement instrument [11] based on the method of "constant current", it is possible to measure the following quantities:

1. the frequency f of the ring vortices;

2. the velocity c inside the flow field (it should be noted that in these measurements the following two quantities are determined because of the measurement technique:

(a) the average velocity $\bar{c}$ and

(b) the variation of velocity c',

where the sum of these two quantities is equal to the flow velocity c;

3. the transport velocity of the vortices, which is obtained by phase measurements using two hot wires and by determining the frequency of the ring vortices. The product of the distance between two ring vortices and the frequency results in the propagation velocity U_v of the ring vortices.

The signals obtained according to the hot wire method are shown in the bottom part of Figure 1. By arranging the figures below each other, it is easier to compare them with photographs taken of the colored thread method. The following results are found.

Figure I first shows a sinusoidal signal, which shows that the formation of the ring vortex begins at this location.

Figure II shows the signal which no longer has a sinusoidal character but has a slight constriction. This signal represents a certain criterion for the existence of ring vortices at this location and that these are not oscillations of a laminar boundary layer. We should point to a paper by O. Wehrmann, which treats the problems associated with hot-wire signals caused by vortices [12].

Figure III shows how two ring vortices are situated with respect to each other, and Figure IV shows the joining of two ring vortices. It is clearly apparent that the frequency of the hot-wire signal is divided in half by this process.

2.3. Flow Measurement Results

Since the results obtained have already been uublished elsewhere [8] and only need to be known for the acoustic processes to be treated later, we will summarize them as follows:

2.3.1. Frequency of the Ring Vortices

The frequency f is proportional to $Re^{3/2}$, where the Reynolds number is formed using the nozzle diameter and the flow velocity in the nozzle (Figure 3).

2.3.2. Velocity Measurements Within the Flow Field

Figure 4 shows the course of the velocity field (lines of average velocity $\bar{c}$) behind the nozzle. It is seen that the flow process immediately behind the nozzle is dominated by flow processes which cannot be described by /104 the time average of the velocity, because the so-called potential core does not extend up to the nozzle outlet. This is especially apparent due to the curvature of the $\bar{c}$ lines behind the nozzle outlet.

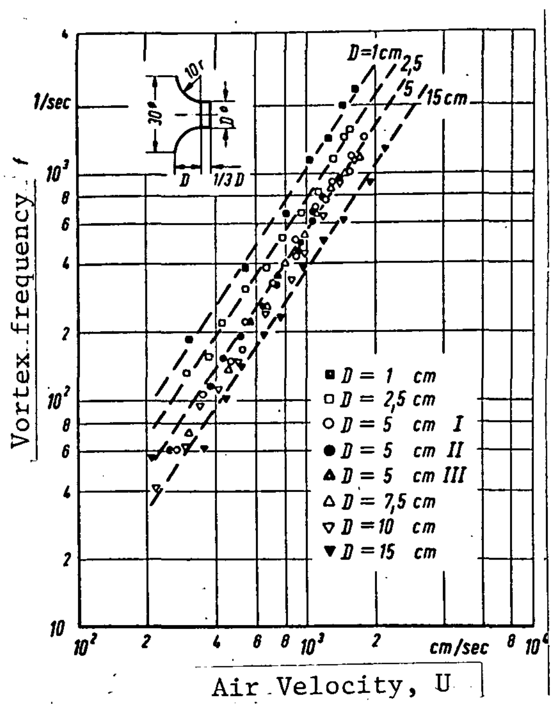

Figure 3. Vortex frequency behind the nozzle outlet.

2.3.3. Vortex Measurements

Figure 5 shows measurements carried out by H. Fabian [13] with ring vortices. The new evaluation method of O. Wehrmann [12] offered the first possibility of determining the vortex intensity of the individual vortices. This intensity increases as the distance to the nozzle is increased, until it reaches a critical size.

3. THE ACOUSTIC INFLUENCE OF THE RING VORTICES

The measurement arrangement (Figure 2) also consists of an

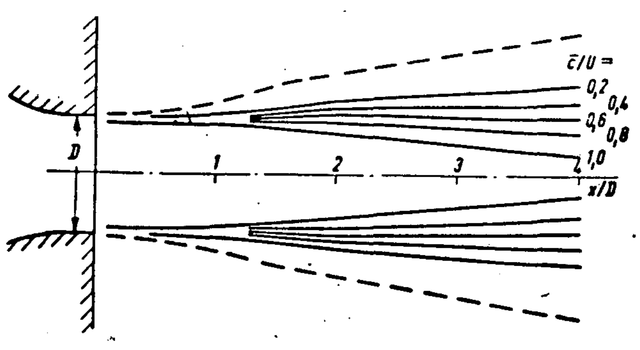

Figure 4. Velocity field of the free jet with 5 cm nozzle. $Re_D = 10,000$.

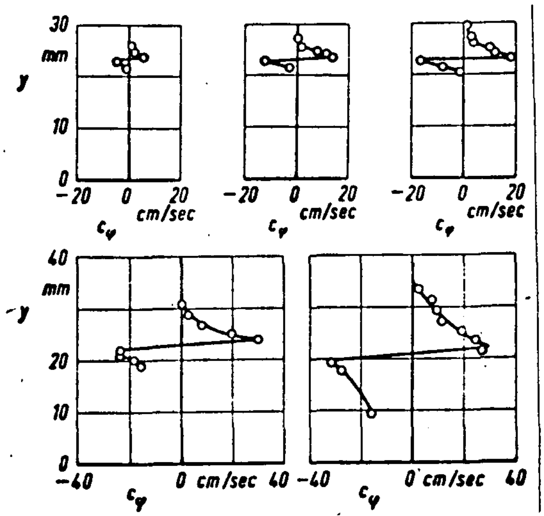

Figure 5. Velocity distribution in vortices for various distances from the nozzle outlet. $Re_D = 5,000$

underpressure chamber. The front side contains the nozzle as well as the hot-wire probe which can be moved within the chamber. A loudspeaker is mounted in front of the nozzle which radiates against the nozzle. The investigations are carried out according to Section 2.3, with acoustic influence. The acoustic pressure can be determined using a measurement microphone.

3.1. Frequency Law

The ordinate in Figure 6 shows the dimensionless quantity $\beta_r \nu / U_\infty^2$ $(\beta_r = 2\pi f_r)$. The abscissa is the flow velocity U. Three curves are shown. The middle line is the frequency which would result without acoustic input (the so-called natural frequency). For example, for a nozzle diameter of 5 cm and a flow velocity of 400 cm/sec, the value $\beta_r \nu / U_\infty^2 = 980 \times 10^{-6}$ is found for the "natural frequency". By means of the acoustical influence, it is possible to increase this value to 1300×10^{-6} or to reduce it to 380×10^{-6}, respectively. In the experiments we found that these are the outer limits of the so-called coherence range. Even if the intensity is increased as

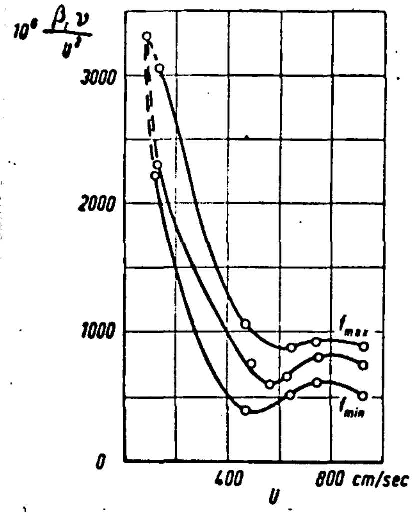

Figure 6. Coherence frequency range of the 5 cm nozzle

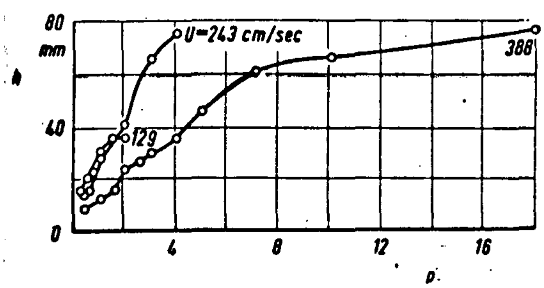

Figure 7. Excitation curves of the 5 cm nozzle as a function of acoustic pressure.

much as possible, it is impossible to vary the frequency of the vortices outside of these limits.

3.2. Influencing of the Vortex Intensity

Figure 7 shows the excitation curves for a nozzle with a diameter of 5 cm. It is found that, if the acoustic pressure is changed, first a region will be present where the intensity of the vortices is proportional to the acoustic pressure, until a certain saturation region is reached. The measurement for the flow velocity 388 cm/sec is of interest. It is seen that approximately ten times the natural vortex intensity can be obtained by acoustic influence, even though the acoustic power is still smaller by four orders of magnitude than that of the main flow. From this it can be concluded that the acoustic influence brings about a control effect in the laminar boundary layer behind the nozzle and thereby makes the rolling-up process of the boundary layer into discrete individual vortices easier. Consequently, a larger intensity is obtained for a shorter elapsed time.

3.3. Influence on the Velocity Field

Figure 8 shows the acoustic influence on the $\bar{c}$ field. The upper part of the figure shows the $\bar{c}$ field without acoustic influence and the lower part

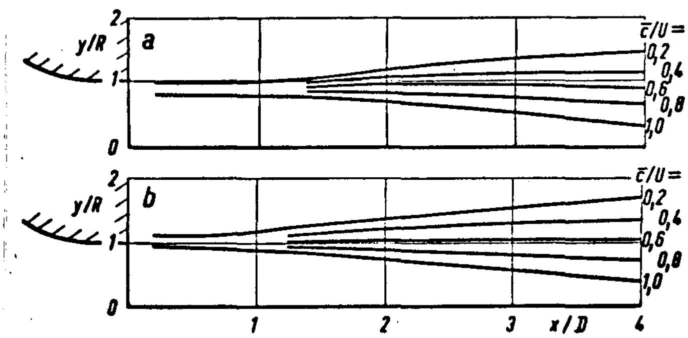

Figure 8. Influence on the velocity field of the 5 cm nozzle.

(a) without acoustical influence;
(b) with acoustical influence
Re_D = 10,000

shows the effect of the acoustic influence in a clear way. There is an increase in the vortex intensity (Section 3.2) for the same path length which is brought about by the acoustic influence. The broadening of the $\bar{c}$ field caused by the vortices occurs much closer to the nozzle, and the entire process is confined to a smaller region behind the nozzle. The low acoustic control energy therefore brings about a displacement of the "natural vortex frequency" as well as an increase in the intensity. /105
This is expressed in the shorter path length of the vortices, because according to previous data [7, 8, 13], the ring vortex decay begins at a certain vortex intensity, which is reached earlier if there is acoustic influence.

3.4. Acoustic Eigen-Excitation of the Vortex Frequencies

Since a certain frequency range can be covered by the externally controlled acoustic influence at the same flow velocity, the question arises as to which of these frequencies will result in the maximum excitation. It can be assumed that this is the so-called "natural frequency", because without acoustic influence it will prevail with the greatest certainty and the highest probability.

The "natural frequency" is recorded in the measurements using a direct display frequency meter. Of course it does not display the frequency of two consecutive ring vortices. Instead, because of its construction it takes an average over a large number of vortices which pass by the hot wire. Therefore, we must always speak of a time average of the frequency due to the always present frequency fluctuations caused by the varying separation times of the individual vortices. It is therefore appropriate to call

$$\bar{f} = \frac{1}{T} \int_{T_1}^{T_2} f(t)\, dT$$

the "natural frequency".

In order to prevent the frequency variation which occurs and to determine the maximum eigen-excitation frequency, we carried out experiments using a feedback circuit. The principle of the measurement is shown in Figure 9. A hot-wire signal is fed to an amplifier, which supplies a loudspeaker located in the underpressure chamber. This measurement arrangement is quite complex and difficult to analyze. It is difficult to test the stability condition equations established by R. Nyquist [14] and the working range of the feedback circuit. Figure 10 shows the results obtained. It is found that the feedback frequency lies within the coherence region curve and approximately follows the same course of the "natural frequency". In addition, the frequency can be measured very accurately. The frequency will be constant if the flow velocity U is held constant. If this frequency is called f, then in this case we have the following if the fluctuations in the "natural frequency" $\bar{f}$ are denoted by f',

$$\frac{1}{T} \int_{T_1}^{T_2} f'\, dT = 0.$$

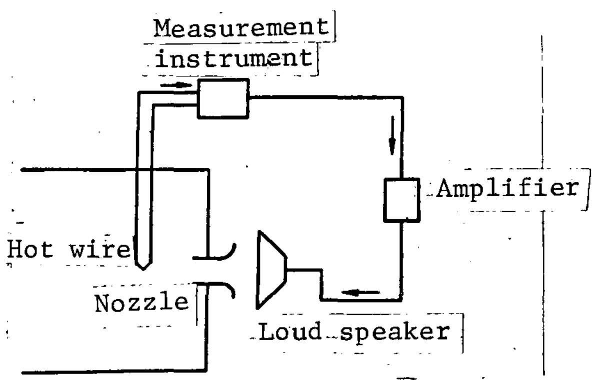

Figure 9. Principle of the feedback method.

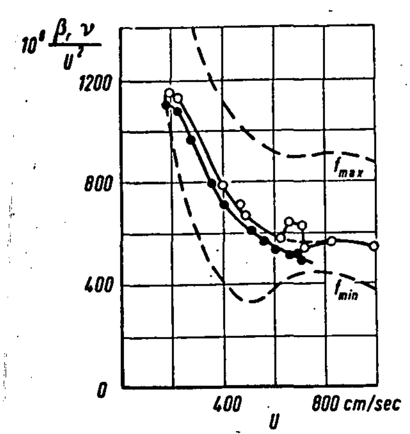

Figure 10. Frequency coherence by feedback.

● - 2.4 cm nozzle; O - 5 cm nozzle.

Figure 10 shows these two curves for the 2.5 cm and the 5 cm nozzle. Both curves have a similar course.

3.5. Comparison with the Stability Curve of a Plate Boundary Layer

Figure 11 shows the comparison with the perturbation frequencies of a plate boundary layer. The ordinate is $\beta_r \nu / U_\infty^2$ again, and the abscissa is the Reynolds number which is formed using the displacement thickness δ^* at the nozzle exit and the flow velocity U_∞. Below this, are the curves for the neutral perturbation frequencies for a plane plate in parallel flow according to calculations by W. Tollmien [15], H. Schlichting [16] and C. Lin [17]. The well-known measurement results of G. B. Schubauer and H. K. Skramstad [18] are grouped along the curve given by C. Lin. /106

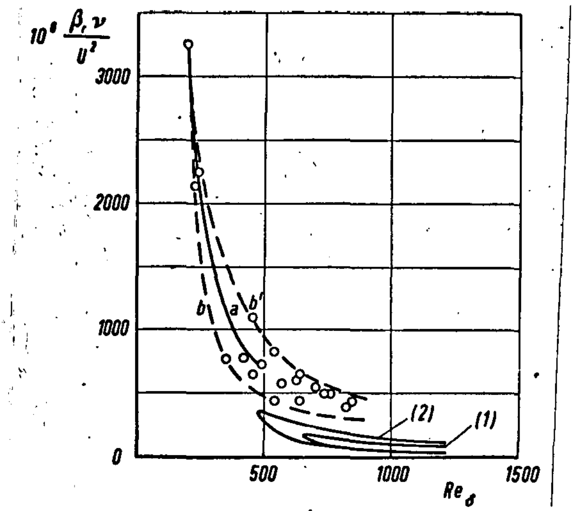

Figure 11. Comparison of the vortex frequencies for the 5 cm nozzle with the stability curve of the plate boundary layer.

(1) according to Tollmien and Schlichting; (2) according to Lin.

The curves shown in the upper half of the figure are valid for frequency measurements of the free jet. The inner curve a gives the course of the "natural frequency" $\bar{f}$, and the other two curves b and b' give the coherence range of the acoustic influence given in Section 3.1.

Strictly speaking, the limiting curve bb' does not have the same meaning as the stability curve of the plate boundary layer. In the case of the plate boundary layer, the curves give the "neutral" perturbations, i.e., neither increasing nor decreasing perturbations. On the other hand, in the free jet only increasing disturbances in the form of increasing ring vortices could be established. The interior of the region has the same meaning in the case of the free jet: flows can only be produced in the circumscribed region.

3.6. The Vortex Transport Velocity

As mentioned in Section 2.2, the transport velocity of the ring vortices can be determined by means of phase measurements using two hot wires. This is quite difficult for the "natural frequency" $\bar{f}$, because due to the fact that the frequency $\bar{f}$ is a function of the time T, the phase angle ϕ must also be a function of the time. Therefore we can only measure

$$\bar{\varphi} = \frac{1}{T} \int_{T_1}^{T_2} \varphi(t)\, dT$$

and plot it on a graph.

It is known that in this case the evaluation can be carried out by means of optical analysis of Lissajou figure photography using a measurement oscillograph. It then becomes possible to determine the correlation coefficient ψ. However, this method is very time consuming.

This is not so if the measurements are performed with acoustic influence. Since in this case

$$\frac{1}{T} \int_{T_1}^{T_2} f'\, dT = 0$$

we must also have

$$\frac{1}{T} \int_{T_1}^{T_2} \varphi'\, dT = 0$$

Thus the wavelength λ of the perturbation can be determined in a simple way. In this case, the wavelength corresponds to the distance between two ring vortices. Obviously we then have

$$U_v = \lambda f.$$

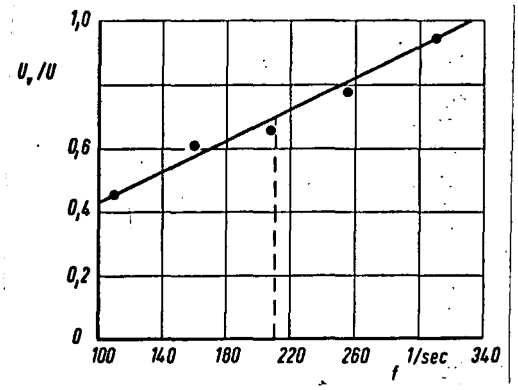

Figure 12. Vortex transport velocity frequency varied acoustically. U = 581 cm/sec.

The measurement results for one velocity U_∞ = 581 cm/sec and a "natural frequency" of 210 Hz is shown in Figure 12 for the 5 cm nozzle.

The most important result is the fact that the wavelength remains constant and thus the vortex transport velocity U_v is a function of the superimposed acoustic frequency.

If we consider the process from the point of view that the free jet core energy dissipation into the quiescent medium depends on the vortex intensity Γ and the vortex transport velocity, then it is apparent that the vortex transport velocity can only be varied within a certain region. This region is clearly apparent when the frequency law is presented according to Figure 6, where a certain coherence range exists corresponding to the variation of the vortex velocity.

DISCUSSION

/108

Dipl.-Ing. K. Kraemer (Göttingen): Did the excited frequencies used for the acoustic feedback change in a continuous or discontinuous way when the flow velocity or the path length were changed? In similar experiments performed by Schubauer and Skramstad, it was not possible to have a continuous transition because of interference (see G. B. Schubauer and H. K. Skramstad: Laminar Boundary Layer Oscillations and Stability of Laminar Flow. J. Aeron. Sci., Vol. 14, 1947).

Dr.-Ing. O. Wehrmann: We did not observe this. There are differences in the acoustic influence capacity because of the differences between the free jet boundary layer and the plate boundary layer.

Dipl.-Ing. K. Kraemer: I would like to refer to the book by Lin about the definition of a concrete Reynolds number for comparison of various nozzle diameters.

Dr.-Ing. O. Wehramm: Two different Reynolds numbers were formed in the work. The first used the nozzle diameter and the second the displacement thickness at the nozzle outlet. In the case of acoustic influence, it is difficult to decide which of the two should be logically used, because there is a possibility that the control effects occur along the nozzle contour and therefore it could be that a third Reynolds number could be important immediately before the control is felt.

Dr.-Ing. F. J. Meister (Düsseldorf): What does the energy balance look like?

Dr.-Ing. O. Wehrmann: The acoustic energy is smaller than the jet energy by 4 orders of magnitude.

Prof. Dr.-Ing. G. Bock (Darmstadt): The work presented is especially important for wind tunnel oscillations, even though we are dealing with another Reynolds number range in this case.

REFERENCES

1. Leconte, J. On the Influence of Musical Sounds on the Flame of a Jet of Coal Gas. Phil. Mag., Vol. 4, No. 15, 1858, pp. 235-250.

2. Brown, G. On Sensitive Flames. Phil. Mag., Vol. 7, 13, No. 82, 1932, pp. 161-195.

3. Brown, G. On Vortex Motion in Gaseous Jets and the Origin of Their Sensitivity to Sound. Proc. Phys. Soc., Vol. 47, 1935, pp. 703-734.

4. Lighthill, M. J. On Sound Generated Aerodynamically. Proc. Roy. Soc., Vol. 211, 1952, pp. 564-587.

5. Lassiter, L. W. and H. H. Hubbard. Experimental Studies of Noise from Subsonic Jets in Still Air. NACA TN 2757, 1952.

6. Powell, A. A Survey of Experiments on Jet Noise. Aircraft Engineering, Vol. 26, No. 299, 1954, pp. 2-9.

7. Domm, U. Über eine Hypothese, die den Mechanismus der Turbulenzentstehung betrifft (A Hypothesis Concerning the Mechanism of Turbulence Production). Report 23 of the German Experimental Agency for Aeronautics, Mülheim (Ruhr), Westdeutscher Verlag, Köln, Opladen, 1956.

8. Wehrmann, O. and R. Wille. Beitrag zur Phänomenologie des laminar-turbulenten Überganges bei kleinen Reynolds-zahlen (Contribution to the Phenomenon of the Laminar-Turbulent Transition for Small Reynolds Numbers). IUTAM Symposium, Freiburg, 1957. To be published soon by Springer-Verlag, Berlin/Göttingen/Heidelberg.

9. Anderson, A. B. C. Structure and Velocity of the Periodic Vortex-Ring Flow Pattern of a Primary Pfeifenton. Acoustical Soc. of America, Vol. 27, 1955, pp. 1048-1053.

10. Anderson, A. B. C. Vortex-Ring Structure-Transition in a Jet Emitting Discrete Acoustic Frequencies. Acoustical Soc. of America, Vol. 28, 1956, pp. 914-921.

11. Wehrmann, O. Methoden und Anwendungen der Hitzdrahtmesstechnik für Strömungsvorgänge (Methods and Applications of Hot-Wire Measurement Techniques for Flow Processes). To be published soon in "Konstruktion".

12. Wehrmann, O. Hitzdrahtmessungen in einer aufgespaltenen Kármánschen Wirbelstrasse (Hot-Wire Measurements in an Bifurcated Karman Vortex Street). Report 43 of the German Experiemntal Agency for Aeronautics, Mülheim (Ruhr), Westdeutscher Verlag, Köln, Opladen, 1957.

13. Fabian, H. Eingereichte Dissertation TU Berlin (Dissertation submitted to Technical University Berlin), not yet published.

14. Nyquist, R. Regeneration Theory. Bell Syst. Techn. Journ., Vol. 11, 1932, pp. 126-147.

15. Tollmien, W. The Production of Turbulence. First Communication. Nachr. Ges. Wiss. Göttingen, Math.-Phys. Klasse, Vol. 21, 1929, pp. 21-44.

16. Schlichting, H. Amplitude Distribution and Energy Balance for Small Oscillations in the Case of Plate Flow. Nachr. Ges. Wiss. Göttingen, Math.-Phys. Klasse, Fachgruppe I, Vol. 1, No. 47, 1935, pp. 47-78.

17. Lin, C. On the Stability of Two-Dimensional Parallel Flows. Quart. Applied Math., Vol. 3, 1945/46, pp. 117-142; 218-234 and 277-301.

18. Schubauer, G. B. and H. K. Skramstad. Laminar Boundary Layer Oscillations and Stability of Laminar Flow. National Bureau of Standards, Research Paper 1772, 1943.

Translated for National Aeronautics and Space Administration under Contract No. NASw 2035, by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93108.